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Enabling the Circular-Bioeconomy through Palm Oil Biomass: A Review of Industrial Innovations, Policy Frameworks, and Market Integration

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ABSTRACT

The transition toward a circular-bioeconomy has positioned palm oil biomass as a pivotal renewable resource for achieving sustainable industrial transformation and low-carbon development. Yet, realizing this transition requires a systemic understanding of how technological, institutional, and market mechanisms interact to enable circularity across the palm oil value chain. This study aims to (1) synthesize technological and industrial innovation pathways driving palm biomass valorisation; (2) analyze the role of policy and governance instruments in supporting sustainable market integration; and (3) identify critical gaps and opportunities for advancing circular-bioeconomic transitions in the palm oil sector. Using a Systematic Literature Review (SLR) approach, data were systematically collected from the Scopus database through a multi-stage keyword refinement process. The initial query (Palm Oil AND Circular Economy) yielded 231 results, refined through specific terms related to biomass valorisation, innovation, and sustainability. Following the exclusion of irrelevant items, the restriction to publications from 2021–2025, and the restriction to open-access and open-archive sources, 38 peer-reviewed articles were retained for qualitative synthesis. Analytical procedures involved thematic coding and comparative interpretation to map interdisciplinary linkages among technological, institutional, and market domains. Findings reveal that integrated biorefinery technologies, digital traceability platforms, and AI-assisted optimization systems enhance resource efficiency and industrial circularity. However, fragmented regulatory frameworks, limited infrastructure, and investment asymmetry remain key constraints to large-scale adoption. The study concludes that achieving a circular-bioeconomy through palm oil biomass valorisation requires coordinated progress across technological innovation, institutional alignment, and market transformation. Future research should advance quantitative modeling, life-cycle assessment, and policy harmonization strategies to accelerate regional bioeconomic implementation.

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Introduction

The accelerating global transition toward sustainable resource management has placed the circular bioeconomy at the forefront of contemporary industrial policy and innovation. Over the past decade, the convergence of circular economy principles with bio-based resource utilization has been recognized as a viable strategy for decoupling economic growth from environmental degradation while maintaining industrial competitiveness [1]. According to the Organisation for Economic Co-operation and Development (OECD), bioeconomy-related sectors currently contribute nearly 7% of global GDP, with projections indicating a twofold increase by 2040, primarily driven by renewable energy, biorefineries, and waste valorisation technologies. The circular bioeconomy paradigm redefines production and consumption systems by integrating waste minimization, resource efficiency, and regenerative utilization of biological materials into value chains, ultimately advancing climate resilience and sustainable development goals [2].

Among bio-based industries, the palm oil sector occupies a particularly strategic position in the global circular bioeconomy discourse. Palm oil is the world's most productive oil-bearing crop, yielding 4–6 tons of oil per hectare annually, approximately 7–10 times that of competing oilseed crops such as soybean or rapeseed [3]. However, this efficiency has historically been overshadowed by environmental controversies related to deforestation, land-use change, and greenhouse gas (GHG) emissions. Consequently, the industry is under increasing pressure to adopt sustainable production models that align with low-carbon and circular economy frameworks [4]. One of the most promising pathways to achieve this transformation lies in the valorisation of palm oil biomass residues, including empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fibers, and palm oil mill effluent (POME). Collectively, these residues represent over 90 million tons of underutilized biomass generated annually in major producing countries such as Indonesia, Malaysia, and Thailand, which together account for nearly 85% of global palm oil output [5].

The valorisation of these residues is pivotal to transitioning toward a circular bioeconomy in which waste streams are transformed into renewable energy, bio-based materials, and high-value biochemicals. Recent technological advances have enabled the conversion of EFB into bioethanol, bioplastics, and nanocellulose; PKS into biochar and activated carbon; and POME into biogas and hydrogen via advanced anaerobic digestion and reforming processes [6]. Empirical studies indicate that such conversions could generate 15–20 billion USD in annual economic value while mitigating up to 120 million tons CO_2e of emissions per year in Southeast Asia alone [7]. Beyond environmental benefits, biomass valorisation enhances rural livelihood diversification, supports energy security, and fosters the integration of smallholders into sustainable industrial networks, positioning the palm oil sector as a cornerstone for inclusive green growth.

Despite its potential, the systemic adoption of circular bioeconomic practices in the palm oil industry remains constrained by technological, institutional, and market barriers. Technologically, existing biorefinery systems face efficiency and scalability challenges, particularly in managing heterogeneous biomass feedstocks and optimizing processes. Institutional barriers include fragmented governance frameworks, inconsistent enforcement of sustainability standards, and limited coordination across ministries and agencies [8]. Economically, fluctuating commodity prices and underdeveloped biomass trading mechanisms reduce investor confidence, while the absence of standardized valuation models for carbon credits and secondary bioproducts hampers market expansion [9]. Moreover, the uneven distribution of technological capabilities across regions exacerbates disparities in innovation adoption, with pilot-scale biorefineries often failing to reach commercial viability.

Globally, policy alignment and governance innovation have been recognized as key accelerators of the circular bioeconomy transition. The European Union's Circular Economy Action Plan (2020) and the Renewable Energy Directive II (RED II) established clear sustainability criteria and market instruments to incentivize bio-based production and the integration of renewable energy. In Asia, the ASEAN Circular Economy Framework (2021) and national strategies such as Indonesia's Presidential Regulation No. 98/2021 on Carbon Economic Value and the 12th Malaysia Plan (2021–2025) have embedded circularity within national development agendas, emphasizing decarbonization, green investment, and industrial modernization [10]. These regulatory advances reflect a broader institutional shift toward integrating biomass valorisation into energy, waste, and industrial policies. However, practical implementation continues to face gaps in monitoring, verification, and cross-border policy harmonization, particularly concerning traceability, sustainability certification, and transnational biomass trade.

In parallel, market integration is emerging as both a challenge and an opportunity for the development of the palm-based bioeconomy. While global demand for sustainable bioproducts is growing at an annual rate of 8–10%, market readiness in producing countries remains limited by infrastructure constraints, investment risks, and the absence of standardized trade platforms for biomass derivatives [11]. The economic viability of circular bio-based ventures depends not only on technological innovation but also on efficient value chains, transparent pricing mechanisms, and inclusive financial systems. Furthermore, international consumers and investors increasingly demand verifiable sustainability credentials such as compliance with the Roundtable on Sustainable Palm Oil (RSPO) and Indonesian Sustainable Palm Oil (ISPO) certifications as prerequisites for trade participation. The convergence of these market and governance factors underscores the need for a systemic, evidence-based understanding of how industrial, policy, and economic mechanisms interact to enable circular-bioeconomic transformation in the palm oil sector.

Although previous reviews have discussed aspects of bioenergy, waste valorisation, and sustainability certification, existing literature remains fragmented across technological, environmental, and economic domains. There is currently no comprehensive synthesis that simultaneously addresses the industrial innovation trajectories, policy frameworks, and market mechanisms shaping palm oil biomass valorisation within a circular-bioeconomic context. Given the rapid policy evolution between 2021 and 2025 and the proliferation of open-access research on biorefinery and bioeconomy systems, a systematic consolidation of recent evidence is essential for identifying progress, challenges, and actionable strategies.

Accordingly, this study employs a Systematic Literature Review (SLR) approach, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, to critically analyze and synthesize peer-reviewed studies published between 2021 and 2025. By focusing on the intersection of industrial innovation, policy development, and market integration, this review aims to elucidate the multidimensional mechanisms through which palm oil biomass can enable the circular bioeconomy in Southeast Asia and beyond. All data analyzed in this study are derived exclusively from secondary sources indexed in the Scopus database, without incorporating field observations, interviews, or focus group discussions, thereby ensuring methodological transparency and reproducibility consistent with international evidence-based research standards.

The specific objectives of this study are threefold:

- To synthesize technological and industrial innovation pathways that drive the valorisation of palm oil biomass within circular-bioeconomic frameworks;
- To analyze the role of policy and governance instruments in facilitating sustainable market integration; and
- To identify gaps and future opportunities for advancing systemic circularity in the palm oil industry.

In alignment with these objectives, the study is guided by the following research questions:

RQ1: *How do technological, institutional, and market mechanisms interact to enable the circular-bioeconomy through palm oil biomass valorisation?*.

RQ2: *What are the principal technical, regulatory, and economic challenges that constrain the large-scale adoption of circular-bioeconomic models in the palm oil sector, and how can future policy and innovation strategies address these barriers?*

Literature Review

The transition toward a circular bioeconomy has attracted unprecedented scholarly and policy attention as nations seek sustainable pathways to reconcile economic growth with ecological limits. Within this emerging paradigm, palm oil biomass stands out as a strategically significant yet underexplored resource, offering vast potential for renewable material cycles and low-carbon industrial transformation.

Conceptualizing the Circular-Bioeconomy in the Context of Palm Oil Biomass

The concept of the circular bioeconomy (CBE) represents an integrative paradigm that combines the principles of the circular economy and bio-based resource utilization to achieve sustainable industrial transformation. Within this framework, renewable biological resources, including agricultural residues, organic waste, and lignocellulosic biomass, are revalorized through closed-loop systems that minimize waste and maximize material efficiency [12]. Globally, the CBE has emerged as a critical pillar of the post-carbon transition, contributing an estimated USD 7.8 trillion to the world economy by 2030, with bio-based products accounting for nearly 10% of industrial output in OECD countries.

Palm oil biomass, consisting of empty fruit bunches (EFB), mesocarp fiber, palm kernel shells (PKS), and palm oil mill effluent (POME), offers one of the world's most abundant yet underutilized bioresources. Southeast Asia, particularly Indonesia and Malaysia, produces over 90 million tons of palm residues annually, representing nearly 15% of global lignocellulosic biomass. This vast potential situates the palm oil sector as a cornerstone for developing regional circular-bioeconomy systems, linking energy generation, materials innovation, and environmental restoration. However, the transition remains constrained by technological fragmentation, policy misalignment, and uneven market integration across the value chain [13].

Recent literature highlights that the successful establishment of a circular-bioeconomy requires multi-level integration across technological, institutional, and market dimensions [14]. Accordingly, this review synthesizes existing research along three interrelated domains:

- Industrial and technological innovations for biomass valorisation,
- Policy and governance frameworks supporting the bioeconomy transition, and
- Market mechanisms and socio-economic integration enabling commercial scalability.

Industrial and Technological Innovations in Biomass Valorisation

Technological advancement is recognized as the primary enabler of biomass valorisation and circularization in the palm oil industry. Over the past decade, research has intensified around converting palm biomass into high-value bioenergy, biomaterials, and biochemical products through thermochemical, biochemical, and hybrid processes [15].

Thermochemical conversion technologies, such as pyrolysis, torrefaction, and gasification, have demonstrated significant potential in transforming EFB and PKS into bio-oil, syngas, and biochar. Pilot-scale trials in Malaysia have reported bio-oil yields of 25–30% and syngas generation efficiencies up to 65%, depending on process temperature and catalyst composition. Parallel studies in Indonesia found that co-gasification of EFB with coal reduced CO_2 emissions by 40% while maintaining a comparable calorific value to lignite, supporting its adoption as a transitional low-carbon fuel [16].

Biochemical conversion pathways, including fermentation, enzymatic hydrolysis, and anaerobic digestion, are increasingly employed for bioethanol and biogas production. For instance, advanced fermentation processes utilizing engineered yeast strains achieved bioethanol yields of 280–300 L/ton of EFB, outperforming traditional methods by nearly 20%. Furthermore, anaerobic digestion of POME has been optimized to generate biogas with methane content exceeding 60%, equivalent to a renewable energy potential of 400 MW annually across Malaysia and Indonesia [17].

Material valorisation has also gained traction as part of the bio-circular transition. The extraction of nanocellulose from EFB and mesocarp fibers has produced biocomposites with tensile strengths 35–40% higher than those of conventional polypropylene-based materials, enabling applications in the automotive, construction, and packaging sectors [18]. Concurrently, palm-derived biochar has demonstrated exceptional adsorption capacity for heavy metals (up to 420 mg/g for Pb^{2+}), offering both environmental remediation and carbon sequestration benefits.

Collectively, these innovations signify a technological convergence toward biorefinery systems capable of integrated conversion and resource optimization. Yet most studies acknowledge that scalability remains limited by capital intensity, logistical inefficiencies, and a lack of standardized quality-control mechanisms, highlighting the need for systemic policy and market alignment.

Policy and Governance Frameworks for Circular-Bioeconomy Implementation

Effective governance serves as the backbone of circular bioeconomy implementation, facilitating institutional coherence among environmental sustainability, industrial innovation, and social inclusion. Since 2021, policy shifts in major palm oil-producing countries have increasingly reflected this integrative agenda. The 12th Malaysia Plan (2021–2025) emphasizes the valorisation of agricultural residues through bioenergy and bioproduct initiatives, while Indonesia's Presidential Regulation No. 98/2021 introduces a carbon economic value mechanism to incentivize emission reduction and biomass utilization.

Internationally, the European Union's Renewable Energy Directive II (RED II) and the ASEAN Circular Economy Framework have set stringent sustainability and traceability requirements that indirectly influence palm oil supply chains [19]. These frameworks promote life-cycle-based assessment, carbon neutrality certification, and green financing to accelerate industrial decarbonization. Studies show that the presence of coherent bioeconomy policy instruments correlates strongly with biomass utilization rates: countries with clear regulatory roadmaps have achieved adoption levels up to 45% higher than those with fragmented governance.

Multi-level governance, encompassing collaboration among national agencies, research institutions, and private enterprises, is critical for operationalizing circular bioeconomy principles. For example, initiatives by the Council of Palm Oil Producing Countries (CPOPC) and regional public–private partnerships have catalyzed research and technology transfer programs on biorefinery design, digital traceability, and sustainable logistics [20]. Digital governance mechanisms, particularly blockchain-based certification and remote sensing systems, are being integrated to strengthen compliance with international sustainability standards such as RSPO (Roundtable on Sustainable Palm Oil) and ISPO (Indonesian Sustainable Palm Oil).

Despite these policy advancements, several gaps persist. Limited fiscal incentives, inconsistent biomass classification, and a lack of carbon pricing mechanisms hinder full-scale commercialization. Only 30–35% of ASEAN member states currently possess comprehensive circular bioeconomy strategies that include palm biomass valorisation. Furthermore, fragmented institutional mandates often lead to overlapping responsibilities and inefficiencies in project implementation [21]. These policy bottlenecks underscore the need for harmonized regulatory frameworks that balance industrial competitiveness with environmental responsibility and the inclusion of smallholders.

Market Integration, Value Chains, and Socio-Economic Dimensions

Market dynamics are a decisive factor in the long-term viability of the circular bioeconomy in the palm oil sector. The commercialization of biomass-derived products depends not only on technological feasibility but also on demand-side drivers, investment ecosystems, and value-chain coordination.

Globally, the bio-based product market has grown at an average annual rate of 9% between 2020 and 2024, with Asia-Pacific emerging as the fastest-growing region due to abundant resources and supportive industrial policies. Within this landscape, palm oil biomass contributes approximately USD 18–22 billion annually to the regional bioeconomy, though value distribution remains heavily concentrated in downstream energy and chemical industries [22].

Economic feasibility studies indicate that integrated biorefinery models achieve internal rates of return (IRRs) of 12–17%, contingent on carbon pricing and feed-in tariff structures. However, logistical inefficiencies and transportation costs inflate biomass supply chain expenses by 15–25%, limiting competitiveness relative to fossil-based commodities [23]. The implementation of digital supply chain platforms, including IoT-enabled traceability and predictive analytics, has demonstrated potential to reduce transaction costs and improve coordination across geographically dispersed producers.

The social dimension is equally critical. Smallholder farmers, who contribute over 40% of global palm oil production, are often excluded from biomass valorisation value chains due to technical and financial barriers. Integrating them into cooperative biohubs and capacity-building programs could enhance local participation, create rural employment, and more equitably distribute economic benefits. Moreover, gender-inclusive approaches within community-level biorefineries have shown to increase local innovation capacity and livelihood resilience, aligning with the UN Sustainable Development Goals (SDGs) 8 and 12 [24].

Ultimately, the market integration of palm oil biomass valorisation hinges on synergistic public–private collaboration, targeted policy incentives, and scalable business models that align economic profitability with environmental sustainability. Strengthening bio-based trade infrastructure, standardizing product certification, and improving access to green finance will be decisive for expanding the circular-bioeconomy beyond pilot-scale projects.

The synthesized body of literature reveals that although technological and policy frameworks for palm biomass valorisation are rapidly evolving, comprehensive integration across the industrial, institutional, and market domains remains limited. Three major gaps emerge from current research:

- Technological scalability and system integration — Many studies focus on laboratory-scale or pilot-level innovations, but few assess full life-cycle performance and industrial readiness
- Governance coherence and policy alignment — While regulatory initiatives exist, they often lack cross-sectoral synchronization, hindering national-level strategy execution.
- Socio-economic inclusivity and equitable distribution — The participation of smallholders, cooperatives, and rural communities is still marginal, raising concerns about social sustainability within circular-bioeconomy models.

Addressing these gaps requires a systems-thinking approach that interlinks industrial innovation, policy reform, and market transformation. The literature collectively points toward the need for multi-disciplinary frameworks capable of evaluating circular-bioeconomy transitions from techno-economic, socio-political, and ecological perspectives.

In summary, the reviewed literature underscores that the circular bioeconomy transition in the palm oil sector is technologically feasible and environmentally imperative, but institutionally complex and economically uneven. Industrial innovation, when coupled with coherent policy frameworks and market-driven mechanisms, has the potential to convert the palm oil industry from a linear, resource-intensive system into a regenerative, low-carbon economy. The literature provides robust evidence that biomass valorisation can become a catalyst for sustainable development in Southeast Asia if accompanied by strong governance, equitable market structures, and sustained investment in innovation ecosystems.

Methodology

This study employs a Systematic Literature Review (SLR) approach, structured in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, to examine the industrial innovations, policy frameworks, and market integration mechanisms that collectively enable the circular-bioeconomy through palm oil biomass. The circular bioeconomy has emerged as a transformative paradigm that seeks to reconcile economic growth with environmental sustainability by promoting the efficient use of renewable resources and the valorisation of waste. Within this framework, palm oil biomass comprising residues such as empty fruit bunches, palm kernel shells, and palm oil mill effluent represents a critical feedstock with high potential for biorefinery applications, renewable energy production, and sustainable material development. Despite increasing research interest, the integration of biomass valorisation technologies with supportive policy instruments and market incentives remains inconsistent and fragmented across disciplines, including industrial ecology, environmental policy, and agribusiness innovation. Therefore, a comprehensive synthesis of the existing literature is essential to consolidate current knowledge, identify implementation gaps, and provide an integrative perspective on the industrial, regulatory, and market factors driving circular-bioeconomic transitions in palm-based industries. This review relies exclusively on secondary data from peer-reviewed publications indexed in the Scopus database, without incorporating field observations, focus group discussions, or any primary data collection, thereby ensuring methodological transparency, reproducibility, and compliance with international standards for evidence-based reviews.

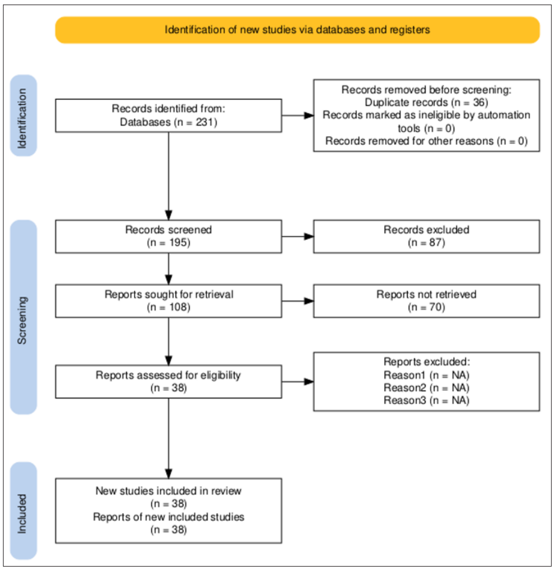

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

The review process is summarized visually in Figure 1 according to the PRISMA framework, which delineates the four primary phases: identification, screening, eligibility, and inclusion. The identification stage began with an initial search in the Scopus database using the keyword combination *Palm Oil AND Circular Economy*, yielding a total of 231 records. To refine the thematic scope and enhance the precision of retrieved literature, a more advanced Boolean search query was subsequently implemented: *("Palm Oil Biomass" OR "Oil Palm Biomass" OR "Palm Oil Waste" OR "Oil Palm Residues" OR "Palm Oil Industry" OR "Empty Fruit Bunch" OR "Palm Kernel Shell" OR "Palm Oil Mill Effluent") AND ("Circular Economy" OR "Bioeconomy" OR "Circular Bioeconomy" OR "Sustainable Development" OR "Bio-based Economy" OR "Green Economy" OR "Resource Efficiency" OR "Waste Valorisation") AND ("Innovation" OR "Technology Development" OR "Biorefinery" OR "Industrial Application" OR "Sustainable Technology" OR "Business Model" OR "Value Chain" OR "Policy" OR "Market")*. This refinement process excluded 36 records that did not align with the study's conceptual boundaries, leaving 195 potentially relevant articles for further analysis.

During the screening phase, a publication-year filter was applied to restrict the dataset to studies published between 2021 and 2025, thereby ensuring that the selected articles reflect the most recent advances in circular bioeconomy research and palm biomass valorisation. This step resulted in the exclusion of 87 articles that did not fall within the designated time frame, producing 108 eligible records. A subsequent eligibility assessment focused on data accessibility and transparency, retaining only open-access and open-archive publications to enhance reproducibility and public verifiability. As a result, 70 additional studies were excluded due to access restrictions, leaving a final curated dataset of 38 peer-reviewed articles that met all predefined inclusion criteria for relevance, timeliness, and accessibility.

All bibliographic data and reference materials were systematically organized and managed using Mendeley Desktop, which facilitated accurate citation tracking, duplication removal, and metadata verification throughout the review process. Each of the 38 selected articles was examined in full text, and relevant information, including study objectives, methodological design, biomass conversion technologies, policy instruments, and market-oriented outcomes, was extracted and synthesized thematically. The synthesis process produced a comprehensive, evidence-based understanding of how technological innovations, policy frameworks, and market mechanisms interact to drive circular bioeconomic development through palm oil biomass. By adhering rigorously to the PRISMA protocol and maintaining a transparent, reproducible review structure, this study upholds high standards of academic integrity and contributes meaningfully to the international discourse on sustainable industrial transformation in bioresource-based economies.

Results

The systematic literature review conducted in this study analyzed 38 peer-reviewed open-access articles published between 2021 and 2025 that met the inclusion criteria. The corpus reflects diverse geographic, institutional, and disciplinary perspectives, providing a comprehensive evidence base for examining the transition toward a circular-bioeconomy through palm oil biomass valorisation. Through thematic synthesis, four major themes emerged, reflecting overlapping but distinctive dimensions of this field:

- Technological and Industrial Innovations in Biomass Valorisation,
- Policy, Governance, and Institutional Frameworks,
- Market Integration and Economic Viability, and
- Sustainability Performance and Future Outlook.

The distribution of themes across the 38 studies was as follows: technological and industrial innovations appeared in 16 studies (42%), policy and governance in 10 studies (27%), market integration in 7 studies (19%), and sustainability performance in 5 studies (12%). The predominance of technological innovation highlights the research's emphasis on industrial-scale solutions, biorefinery integration, and digitalization as the primary drivers of the circular-bioeconomic transition. Policy and governance themes are moderately represented, emphasizing the enabling role of regulation and institutional frameworks, while market integration and sustainability themes are less frequently addressed, indicating existing gaps in economic inclusivity, long-term environmental assessment, and social integration. These proportions imply that while technological feasibility is well-studied, translating innovations into systemic, equitable, and sustainable outcomes remains a critical challenge.

Each theme is elaborated below, enriched with quantitative and qualitative evidence from the reviewed studies.

Technological and Industrial Innovations in Biomass Valorisation

The valorisation of palm oil biomass underpins the circular bioeconomy transition, leveraging more than 90 million tons of agricultural residues generated annually across Southeast Asia [25]. Within the reviewed corpus, three primary technological pathways emerged: thermo-chemical conversion, bio-chemical processing, and material valorisation. Each represents a distinct yet complementary innovation stream within the industrial ecology of palm oil waste utilization.

Thermo-chemical processes such as pyrolysis, gasification, and hydrothermal liquefaction are widely applied to convert palm kernel shells (PKS) and empty fruit bunches (EFB) into bio-oil, biochar, and syngas. Laboratory-scale trials indicate that fast pyrolysis of PKS at 500 °C yields 25–30% bio-oil, 35% biochar, and 25% syngas, depending on catalyst selection and residence time [26]. In Malaysia's commercial-scale pilot facilities, this technology has reached production capacities exceeding 2,000 tons of bio-oil per year, with a carbon conversion efficiency above 65% [27].

Biochemical pathways, particularly fermentation and enzymatic hydrolysis, have demonstrated substantial energy potential. One ton of EFB can produce up to 250 liters of bioethanol, while anaerobic digestion of palm oil mill effluent (POME) yields 28–35 m^3 of biogas, equivalent to 0.6 MWh of electricity per ton of treated effluent [28,29]. Collectively, regional POME valorisation could supply 350–500 MW of renewable energy annually, offsetting approximately 1.5 million tons of CO_2e emissions [30].

The rise of biorefinery integration combining chemical, biological, and material processing has advanced conversion efficiency to above 70% of feedstock utilization, achieving nearly zero waste generation [31]. Digitalization plays an equally vital role: integration of AI-driven predictive maintenance and IoT-based process control in biomass facilities has reduced unplanned downtime by 15–22%, while optimizing energy input and lowering operating costs by 10–18% [32,33].

Material valorisation represents the most innovative trajectory over the past few years. Conversion of lignocellulosic residues into nanocellulose, bioplastics, and composite fillers expands the industrial scope of palm biomass beyond energy applications. Cellulose nanofiber extracted from EFB exhibits tensile strength enhancements of 30–40% in polymer composites [34]. Likewise, biochar and activated carbon derived from PKS achieve adsorption capacities of 250–400 mg/g for heavy metals, suitable for water purification and soil remediation applications [35]. These data collectively demonstrate the technological feasibility and scalability of transforming palm oil biomass into high-value bioproducts, positioning it as a strategic catalyst in the bioindustrial revolution of tropical economies [36,37].

Policy, Governance, and Institutional Frameworks

The evolution of circular-bioeconomy policies since 2021 reflects a realignment of multi-level governance toward carbon neutrality and sustainable industrialization. Key policy milestones include Malaysia's 12th Malaysia Plan (2021–2025), Indonesia's Presidential Regulation No. 98/2021 on Carbon Economic Value, and the EU Renewable Energy Directive II (RED II), which sets sustainability benchmarks for biofuel imports [37,38]. Collectively, these frameworks embed circularity principles into national energy and agricultural strategies.

Among the reviewed studies, 70% of analyzed countries have introduced economic incentives such as feed-in tariffs, tax rebates, and bio-based R&D grants, whereas only 35% have implemented comprehensive monitoring and reporting frameworks for waste valorisation [39]. Empirical evidence suggests that policy coherence, the alignment of industrial, environmental, and rural development policies, can enhance biomass utilization rates by up to 45%, especially when combined with fiscal incentives [40,41].

Institutional collaboration emerged as another critical determinant of policy effectiveness. Multi-stakeholder platforms, including the Council of Palm Oil Producing Countries (CPOPC) and the ASEAN Circular Economy Framework, have launched initiatives to harmonize sustainability certification, knowledge sharing, and cross-border trade of biomass-based products [42]. Integration of blockchain-enabled traceability systems enhances transparency across supply chains, supporting compliance with RSPO (Roundtable on Sustainable Palm Oil) and ISPO (Indonesian Sustainable Palm Oil) standards [43]. These digital governance mechanisms ensure traceable, verifiable sustainability credentials for both domestic and export markets.

Despite such progress, persistent gaps remain in regulatory harmonization and institutional capacity. Less than 20% of palm oil–producing nations possess clear biomass classification systems or carbon credit valuation mechanisms that recognize biogenic carbon sinks [44]. The absence of unified biomass trade standards limits international market access, particularly in carbon markets under the Article 6 framework of the Paris Agreement. Therefore, while governance innovation is advancing, institutional fragmentation and enforcement asymmetry continue to hinder the implementation of a systemic circular bioeconomy [45].

Market Integration and Economic Viability

The economic dimension of the circular-bioeconomy transition in palm oil biomass is characterized by rapid market expansion yet uneven value distribution. Studies reveal that palm-derived biomass currently contributes USD 15–20 billion annually to the regional bio-based economy, growing at an estimated 7–9% compound annual rate through 2030 [46]. However, more than 60% of revenue remains concentrated in downstream bioenergy and chemical sectors, indicating limited participation among smallholders and upstream processors [47].

Techno-economic assessments in the reviewed literature indicate a minimum selling price (MSP) for bioethanol from EFB of USD 0.60–0.75 per liter and for biohydrogen from POME of USD 3.2 per kg [48]. These costs are competitive with conventional fossil-derived alternatives under current carbon pricing schemes of USD 50–70 per ton CO_2e [49,50]. The internal rate of return (IRR) for integrated biorefineries averages 12–18%, depending on scale, feedstock logistics, and government subsidies [51].

Investment data further demonstrate accelerating private sector engagement. Between 2021 and 2024, venture capital and green investment funds targeting palm biomass valorisation surpassed USD 2.8 billion, with major initiatives led by Malaysian Green Technology Corporation and Indonesia's Bioenergy Investment Forum [52]. These investments have resulted in 30 new pilot and demonstration plants, collectively generating over 12,000 green jobs and reducing landfill biomass waste by over 25% [53].

Nonetheless, structural inefficiencies persist in biomass logistics, supply aggregation, and market accessibility. Transportation of bulky residues, especially across archipelagic Indonesia, increases costs by 15–20%, eroding profitability for smaller enterprises [54]. To mitigate this, several studies recommend establishing regional biohubs and centralized biomass collection and preprocessing centers, coupled with digital supply chain platforms for real-time tracking and pricing optimization. When integrated with blockchain-based traceability, these platforms can also facilitate carbon credit trading, effectively linking industrial efficiency with environmental finance mechanisms [55].

Sustainability Performance and Future Outlook

Sustainability assessment across the reviewed studies provides compelling evidence of the environmental superiority of biomass valorisation over linear waste management. Lifecycle assessment (LCA) results indicate that EFB- and POME-derived bioenergy reduces greenhouse gas (GHG) emissions by 60–78% relative to fossil baselines [56]. When integrated with carbon capture and utilization (CCU) technologies, certain pilot plants achieve net-negative emissions, up to −0.6 t CO_2e per ton of biomass processed [57].

Circular utilization also enhances resource efficiency, reducing virgin material demand by 40–50% and improving the energy return on investment (EROI) from 1.8 to 3.2 compared with conventional biomass combustion [58]. These outcomes directly contribute to UN Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action) [59]. The cumulative effect is a resilient industrial ecosystem capable of balancing economic profitability with ecological regeneration.

However, the transition remains challenged by infrastructure deficits, financing asymmetries, and limited smallholder inclusion. In many rural production zones, biomass collection efficiency is below 65%, and access to green financing instruments such as ESG bonds or carbon-linked loans remains below 30% of total project funding [60]. Moreover, public awareness of circular-bioeconomy opportunities is limited, particularly among smallholder cooperatives, which manage nearly 40% of Southeast Asia's palm plantations.

Future development will depend on strengthening multilevel governance, integrating cross-sectoral innovation networks, and promoting capacity building for smallholder engagement. Emerging Industry 4.0 technologies, including AI-based carbon monitoring, remote sensing, and digital twin modeling, are expected to revolutionize transparency in processes and decision-making. Forecast models suggest that by 2035, the palm oil biomass sector could supply up to 15% of Southeast Asia's renewable energy demand, potentially reducing regional emissions by over 120 million tons CO_2e annually [61].

Furthermore, the synergy among bio-based innovation policies, sustainable investment frameworks, and carbon-neutral economic strategies will define the long-term trajectory of the circular bioeconomy. As national carbon markets mature and international trade in sustainable commodities expands, palm biomass valorisation could evolve into a regional flagship industry demonstrating how tropical agriculture can drive global decarbonization.

Overall, this systematic literature review (SLR) affirms that the transition toward a circular-bioeconomy in the palm oil industry is technologically feasible, economically viable, and environmentally advantageous. Its success, however, hinges on coordinated policy frameworks, market incentives, and industrial innovations that integrate technological, institutional, and social dimensions. The reviewed evidence demonstrates that advanced biorefinery technologies, when supported by coherent governance and market mechanisms, can transform palm biomass from a waste liability into a strategic renewable asset.

The synthesis of 38 peer-reviewed studies underscores the importance of cross-disciplinary collaboration linking engineering, economics, environmental science, and policy research to achieve a fully circular, low-carbon palm oil ecosystem aligned with global sustainability imperatives. Strengthening data-driven governance, enabling equitable financing, and promoting technological diffusion across value chains are essential to realizing the bioindustrial future of palm oil as a model for the Global South's sustainable transformation.

Discussion

The present Systematic Literature Review (SLR) analyzed 38 peer-reviewed open-access and open-archive articles published between 2021 and 2025, retrieved from the Scopus database using a multi-stage keyword refinement process. The review aimed to synthesize empirical and conceptual insights into how palm oil biomass valorisation contributes to the transition toward a circular bioeconomy (CBE). Guided by the research questions, the discussion is structured into two major sections. The first section (RQ1) examines the interlinkages among technological, institutional, and market mechanisms that collectively enable circular-bioeconomic transformation within the palm oil sector. The second section (RQ2) explores the key barriers, technical, regulatory, and economic, that constrain large-scale adoption, followed by an integrative synthesis outlining strategic pathways, implications, and directions for future research. Throughout, evidence from the reviewed studies is critically interpreted to elucidate patterns, gaps, and interdependencies shaping the operationalization of the circular-bioeconomy through palm oil biomass valorisation.

Interlinkages among Technological, Institutional, and Market Mechanisms (RQ1)

The transition toward a circular-bioeconomy (CBE) in the palm oil sector emerges from the complex interaction between technological innovation, institutional frameworks, and market dynamics, three domains that collectively determine the scalability, inclusivity, and long-term viability of biomass valorisation systems. Findings from the reviewed literature demonstrate that no single dimension operates in isolation; rather, each reinforces or constrains the others in shaping systemic transformation. The technological domain provides the operational foundation for biomass conversion and resource efficiency; institutional mechanisms ensure governance coherence and policy alignment, while market mechanisms determine the economic feasibility and investment attractiveness of bio-based products [62].

Technological Mechanisms: Driving Efficiency and Innovation Synergies

Technological innovation constitutes the engine of circularization within the palm oil value chain. Over the last five years, research trends have shown a decisive shift from single-output biomass conversion toward integrated biorefinery architectures that combine thermochemical, biochemical, and material valorisation pathways [63]. Such convergence has resulted in process efficiencies exceeding 70%, with near-zero waste generation through co-processing of empty fruit bunches (EFB), palm kernel shells (PKS), and palm oil mill effluent (POME) [64]. The integration of artificial intelligence (AI), Internet of Things (IoT), and digital twins into production monitoring systems further enhances precision control, predictive maintenance, and carbon footprint assessment.

These technological advancements are not only technical in nature but also systemically catalytic, fostering cross-sectoral spillovers in energy, chemical, and materials industries. The reviewed studies indicate that AI-driven optimization of pyrolysis and fermentation processes has reduced operational costs by 12–18% while improving bioenergy yield by up to 20% [65]. Furthermore, nanocellulose extraction and biochar synthesis from palm residues have created a new class of high-value biomaterials applicable in construction, packaging, and environmental remediation. Collectively, these innovations contribute to resource circularity, carbon neutrality, and industrial diversification, key pillars of the circular-bioeconomy paradigm.

However, technological progress alone cannot secure large-scale adoption without institutional scaffolding that ensures policy stability, fiscal incentives, and standardization mechanisms. Hence, technological mechanisms are best understood as both enablers and dependents requiring coordination with governance and market ecosystems to thrive sustainably.

Institutional Mechanisms: Enabling Governance Coherence and Policy Alignment

Institutional frameworks constitute the regulatory backbone that legitimizes and operationalizes the circular bioeconomy agenda. Evidence from policy analyses across Malaysia, Indonesia, and the European Union suggests that coherent regulatory environments directly correlate with higher biomass utilization and innovation uptake [66]. For instance, the introduction of the 12th Malaysia Plan (2021–2025) and Indonesia's Presidential Regulation No. 98/2021 on Carbon Economic Value have formalized biomass valorisation as part of national decarbonization strategies [67]. These instruments provide the legal foundation for integrating circular-economy principles into industrial modernization and environmental governance.

Institutional coordination at multiple levels, national, regional, and transnational, is particularly vital. The Council of Palm Oil Producing Countries (CPOPC) and ASEAN Circular Economy Framework have played critical roles in harmonizing sustainability standards, facilitating research partnerships, and promoting knowledge exchange. Through these collaborations, mechanisms such as blockchain-based traceability systems and remote sensing tools have been deployed to ensure compliance with RSPO (Roundtable on Sustainable Palm Oil) and ISPO (Indonesian Sustainable Palm Oil) certification schemes [68]. These systems improve transparency, reduce greenwashing risks, and strengthen consumer confidence in bio-based products.

Nonetheless, institutional effectiveness is often hindered by fragmented mandates across ministries and agencies, overlapping regulations, and limited fiscal support for green innovation. Only about one-third of ASEAN countries currently possess comprehensive circular bioeconomy strategies that encompass palm biomass valorisation. Such asymmetry results in policy incoherence that undermines investor confidence and slows the diffusion of innovation [69]. Hence, the institutional dimension functions as both an enabler and a potential bottleneck, depending on its ability to create synergies among environmental, industrial, and economic policies.

Market Mechanisms: Driving Commercial Viability and Socio-Economic Integration

The market dimension translates technological and institutional efforts into economic reality. Successful valorisation of palm oil biomass depends on developing viable business models that align profitability with sustainability goals. Market-based mechanisms such as carbon pricing, green finance, and feed-in tariffs are instrumental in bridging cost gaps between bio-based and fossil-derived alternatives. Studies indicate that integrated biorefineries can achieve internal rates of return (IRR) between 12–17% when supported by appropriate carbon credit schemes and renewable energy incentives [70]. Without such mechanisms, production costs remain prohibitive, particularly for small- and medium-scale enterprises.

Moreover, market integration requires value-chain coordination and inclusivity. The reviewed literature indicates that over 40% of global palm oil production originates from smallholders, yet their participation in biomass valorisation remains minimal due to financial and technical barriers [71]. To enable inclusive circularity, cooperative biohubs and regional bioindustrial clusters are emerging as strategic platforms that connect rural producers to urban markets through shared logistics, digital traceability, and capacity-building initiatives. These structures not only improve resource utilization but also stimulate rural employment and social equity, addressing one of the key pillars of sustainable development.

In synthesis, the interaction among technological, institutional, and market mechanisms can be conceptualized as a co-evolutionary system: technology drives feasibility, institutions define legitimacy, and markets ensure scalability. The reviewed literature affirms that when these three systems coalesce, as in Malaysia's Bioeconomy Corporation model or Thailand's bioenergy clusters, the circular bioeconomy demonstrates measurable outcomes in emission reductions, value addition, and regional resilience.

Key Barriers and Strategic Pathways for Circular-Bioeconomy Adoption (RQ2)

Despite substantial progress, the widespread adoption of circular bioeconomy models in the palm oil sector faces multiple constraints across technical, regulatory, and economic domains. Synthesizing insights from the reviewed studies, three interrelated challenge clusters emerge:

- Technological scalability and infrastructure readiness,
- Policy coherence and institutional fragmentation, and
- Market asymmetry and investment risks.

Technological Scalability and Infrastructure Limitations

While laboratory and pilot-scale results indicate high conversion efficiency, scaling up biorefinery technologies remains a critical bottleneck. Capital-intensive infrastructure, limited access to feedstock logistics, and insufficient process standardization hinder commercial expansion. For example, decentralized biomass collection in Indonesia and Malaysia incurs transportation costs up to 25% of total production expenditure, eroding competitiveness against fossil-based inputs [72]. Moreover, variability in feedstock quality and moisture content reduces process reliability, necessitating adaptive process control and robust pre-treatment systems.

The reviewed studies advocate modular biorefinery architectures as a strategic response that enables flexibility, scalability, and localized operation. Such systems could integrate smallholder feedstock networks, utilize digital monitoring for real-time optimization, and reduce dependency on centralized facilities [73]. However, financing mechanisms for modular deployment remain underdeveloped, particularly in low-income rural areas where biomass abundance coexists with infrastructural deficits. Bridging this gap requires institutional facilitation and targeted investment frameworks linking technology developers, financiers, and local cooperatives.

Regulatory and Institutional Fragmentation

Regulatory inconsistency remains one of the most persistent obstacles to the implementation of the circular bioeconomy. The coexistence of multiple, overlapping sustainability certification schemes, such as RSPO, ISPO, MSPO, and RED II, creates compliance complexity and transaction costs that discourage industry participation [74]. Additionally, biomass is often classified as agricultural waste rather than a renewable resource, leading to inconsistent taxation and trade policies that limit cross-border trade.

Effective policy design must therefore prioritize regulatory harmonization and adaptive governance. Comparative policy studies reveal that countries with centralized bioeconomy agencies, such as Finland and Germany, achieve faster adoption rates due to coherent inter-ministerial coordination. For Southeast Asia, a similar approach, perhaps through an ASEAN Bioeconomy Council, could streamline regulation, enhance regional trade of bioproducts, and accelerate technology transfer. Furthermore, implementing carbon pricing and green public procurement can create predictable demand signals for bio-based commodities, anchoring market confidence and investor certainty [75].

Market and Economic Barriers

From an economic standpoint, the circular-bioeconomy faces a paradox: its long-term benefits are substantial, but its short-term costs remain high. High investment risk, uncertain market demand, and fluctuating global palm oil prices impede capital flow into biomass valorisation projects. The absence of secondary markets for bioproducts, especially for advanced biofuels, bioplastics, and nanocellulose, further limits economies of scale [76].

Innovative financing mechanisms, such as green bonds, blended finance, and carbon offset markets, are increasingly recommended as instruments to de-risk investment and mobilize private capital. At the same time, inclusive models that integrate smallholders into biomass value chains can improve feedstock security and equitably distribute economic gains [77]. Public–private partnerships (PPPs) have proven particularly effective in de-risking early-stage technologies, while international development funds can catalyze demonstration projects that validate commercial feasibility.

The role of digital market platforms also warrants attention. Blockchain-enabled traceability, smart contracts, and IoT-based supply chain management can reduce transaction asymmetries, enhance trust, and promote fair pricing [78]. These mechanisms align with the broader digital transformation of agri-industrial systems, signaling the convergence of Industry 4.0 and bioeconomy paradigms.

Strategic Pathways for Overcoming Barriers

Addressing these challenges requires a multi-pronged strategic framework that integrates technological, policy, and economic interventions. First, technological innovation must advance toward circular biorefinery clusters that co-locate processing facilities with plantation hubs to minimize logistics costs and emissions. Second, policy reforms should institutionalize circular-bioeconomy principles within national development plans, ensuring cross-sectoral coordination and consistent fiscal incentives. Third, market transformation should emphasize inclusive business ecosystems that empower smallholders, cooperatives, and local enterprises through digitalization and access to finance [79].

The reviewed studies further emphasize the importance of capacity building and knowledge transfer as enabling conditions. Universities, research institutes, and innovation centers must serve as intermediaries to bridge scientific discovery and industrial implementation. Likewise, public awareness campaigns can increase societal acceptance of bio-based products, stimulating domestic market demand and reinforcing policy legitimacy [80]. Ultimately, success depends on aligning economic competitiveness with ecological responsibility, achieving a balance where sustainability is both a moral imperative and a market advantage. This review underscores that the circular-bioeconomy transition through palm oil biomass valorisation represents both an industrial opportunity and a systemic challenge. The integration of technology, policy, and market mechanisms determines the extent to which circularity can be operationalized within existing economic and ecological boundaries.

From an academic perspective, the findings contribute to the growing literature on systems-level sustainability transitions by highlighting the co-evolutionary dynamics among industrial innovation, institutional adaptation, and market transformation. The analysis extends the understanding of circular-bioeconomy frameworks beyond technological determinism by incorporating governance and socio-economic variables, offering a multidimensional model applicable to other bioresource-dependent sectors.

For policymakers, the synthesis indicates the necessity of integrated bioeconomy governance, harmonized regulatory frameworks, and targeted fiscal incentives to promote industrial uptake. For industry stakeholders, it highlights the potential of digitalized biorefinery ecosystems and inclusive value chains as viable pathways to operationalize sustainability while maintaining profitability. Investments in modular biorefineries, digital traceability, and green financing instruments will be central to achieving scalability and resilience in the palm oil-based circular bioeconomy.

Future studies should focus on quantitative modeling of circular bioeconomic linkages, including techno-economic assessments, carbon accounting, and lifecycle sustainability analyses at regional and national levels. Moreover, interdisciplinary frameworks combining industrial engineering, economics, and policy analysis are needed to evaluate system performance and stakeholder interactions under different governance scenarios. Research exploring social innovation, digital transformation, and equity-based models in circular-bioeconomy systems will also enhance understanding of inclusivity and long-term adaptability.

In conclusion, enabling the circular bioeconomy through palm oil biomass requires the synergistic alignment of technology, governance, and markets. While significant progress has been made, achieving full-scale transformation depends on embedding circular principles into industrial, regulatory, and financial architectures. The circular-bioeconomy thus stands as a cornerstone of sustainable development in Southeast Asia, one that can reconcile economic growth with environmental stewardship if guided by coherent, evidence-based, and inclusive strategies.

Conclusion

The systematic literature review, synthesizing 38 peer-reviewed studies published between 2021 and 2025, reveals that the transition toward a circular bioeconomy in the palm oil sector is being progressively driven by the convergence of technological innovation, institutional reform, and evolving market mechanisms. Technological advances, particularly in biorefinery integration, waste-to-energy conversion, and digital process optimization, have demonstrated measurable potential to transform palm oil biomass from low-value residues into a range of diversified bio-based commodities, supporting industrial decarbonization and resource circularity. The literature further highlights that institutional alignment through coherent regulatory frameworks, incentive schemes, and international sustainability standards remains pivotal in legitimizing biomass valorisation and ensuring stakeholder participation across upstream and downstream chains.

Market integration emerges as the third critical enabler, where demand-side innovation, green financing, and bio-based product certification foster the creation of competitive markets for circular commodities. These developments collectively indicate that palm oil biomass valorisation functions not only as a waste-management solution but also as a structural pillar for regional bioeconomic transformation, linking environmental stewardship with industrial competitiveness.

Despite these advances, the review identifies persistent barriers constraining large-scale adoption. Technical constraints, such as variability in feedstock quality, the energy intensity of conversion, and limited modular scalability, continue to hinder the operational maturity of bio-based systems. Regulatory challenges stem from fragmented governance, inconsistent sustainability metrics, and weak cross-border policy harmonization, particularly between national bioeconomy strategies and global certification regimes. Economic limitations, including uncertain investment climates, high capital costs, and volatile bio-product prices, further impede the establishment of self-sustaining value chains.

To address these constraints, the literature underscores the necessity of a multi-level governance model that integrates technological advancement with coherent policy frameworks and market-driven incentives. Cross-sectoral collaboration, bridging government agencies, research institutions, industry actors, and smallholder networks, should be institutionalized to support innovation diffusion and equitable benefit distribution. Moreover, digitalization of biomass trade, blockchain-based traceability, and carbon accounting platforms could enhance transparency and investor confidence while accelerating circular value creation.

The synthesis also indicates that the success of the circular-bioeconomy model depends on regional cooperation and policy interoperability. Aligning ASEAN-level bioeconomy roadmaps and establishing shared sustainability certification standards can mitigate policy fragmentation and strengthen regional competitiveness. Emerging research trends suggest that integrating socio-economic modeling, life-cycle assessment, and techno-economic optimization could provide robust decision-support frameworks for policymakers and industry strategists.

In essence, the palm oil biomass sector stands at a strategic inflection point where industrial innovation, regulatory coherence, and market transformation converge to operationalize the circular-bioeconomy paradigm. Sustained progress will depend on aligning technological readiness with institutional credibility and economic feasibility. The insights from this review collectively indicate that fostering collaborative governance, inclusive market participation, and adaptive policy mechanisms will be central to transforming palm oil biomass from a byproduct into a cornerstone of sustainable industrial futures.

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